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Hydrogen Fueling – Infrastructure for Fuel Cell Bus Fleets

European version

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1. Introduction

Major European cities, including London, Paris, Madrid, Copenhagen and Athens, have announced plans to phase out diesel vehicles from roadways in an effort to improve air quality. In support of this, cities are turning to transit agencies and bus operators to be leaders in deploying zero-emission fleet vehicles. Hydrogen fuel cell powered vehicles have the potential to significantly reduce the environmental impact of transportation in comparison to vehicles powered by internal combustion engines.

Figure 1: Fuel Cell Bus Being Refueled With Hydrogen

Demonstration fleets are in operation throughtout Europe and hundreds of fuel cell buses are expected to be deployed in Europe and the rest of the world in the next two to five years. With centralized filling and increasing fleet sizes, the deployment of fuel cell buses is providing an ideal opportunity to reduce the cost of hydrogen infrastructure and fuel.

Hydrogen fuelling stations at bus depots must be capable of providing thousands of kilograms of hydrogen per day within a short overnight refuelling window. Stations will need store high volumes of hydrogen within the footprint of the bus depot and, with public relying on the transit system, the refuelling infrastructure must have ultra-high reliability to keep buses in operation.

Transit agencies and bus operators in Europe are leaders in deploying this hydrogen infrastructure. This paper will provide an overview of the hydrogen supply options available to transit agencies and guide readers in sourcing the appropriate fuelling infrastructure and hydrogen supply for their fuel cell bus fleet.

2. Hydrogen Infrastructure at the Bus Depot

Transit agencies and bus operators refuel their buses at the end of the day within a specific time window to be ready for service the next morning. Deployments around the world have proven fuel cell buses can be fueled safely and efficiently. Transit agencies and bus operators can rely on local industrial gas suppliers to be at the forefront of the development of hydrogen stations for bus fuelling. Options include permanent stations to fuel a fleet of transit buses or temporary installations for technology demonstration programs. Regardless of scale, a fully integrated fuelling solution installed at a bus depot will include two primary systems:

1. Hydrogen generation – or more typically where the production of fuel takes place off-site and is trucked in – bulk hydrogen storage in the form of compressed cylinders or a liquid hydrogen storage tank. Refer to Appendix I for further details regarding these hydrogen supply alternatives.
2. A compression, storage and dispensing (CSD) module to deliver fuel to the vehicle, including the hydrogen compression, high-pressure storage, and dispensing systems. Hydrogen is dispensed to the vehicles at a pressure of 350-bar or 700-bar. Typically, the dispenser is located on a fuelling island in line with normal bus fuelling operations but may sometimes be packaged with the compression and storage systems in a "containerized" CSD module.

Figure 2: Hydrogen Dispenser in Aberdeen, Scotland

When considering the implementation of a hydrogen station, every transit property will be unique with regards to their specific requirements. It is not a one-size-fits-all situation related to budget and schedule for each specific property. The following sections describe three phases that a typical transit agency will work through as the fuel cell electric bus fleet grows from a demonstration to a full-scale deployment. These stages are designed to flexibly expand the hydrogen infrastructure to match the growing fuel cell bus fleet in a measured and economical way.

3. Phase I – Demonstration Fleet (~5 buses)

Transit agencies and bus operators will typically demonstrate one to five fuel cell electric buses before making the strategic decision to expand the fleet. Transit agencies abd operators at this stage in deployment are conducting an initial evaluation of the technology to gain a better understanding of the specific benefits to the operator and the riders. The fuelling infrastructure for this type of demonstration must be temporary or scalable, and not entail substancial changes to the operating environment at bus fuelling facility.

Fuel cell electric buses will typically carry up to 40 kilograms of hydrogen and consume approximately 25 kilograms of hydrogen per day; therefore this station will require a capacity of 125 kilograms per day to fuel up to fixe buses. This volume is too small to justify the investment required for all liquid hydrogen storage or on-site steam methane reforming (converting natural gas into hydrogen).

3.1. Fuelling Solution

The two variable options for a demonstration fleet of this size would be on-site electrolysis (producing hydrogen from water and electricity) or compressed gas delivered and stored in tube trailers. The compressed gas is generated off-site, either from the steam methane reforming or through the capture of by-product waste hydrogen. A CSD module is required to deliver fuel to the vehicle. The block diagram below illustrates the compressed gas delivery fuelling pathway.

With a high pressure (500-700 bar) trailer, it is possible to distrubute 1,500-2,000 kilograms of hydrogen at a time. Depending the consumption and site requirements, the trailer may be parked at the site or transferred to an onsite storage tank.

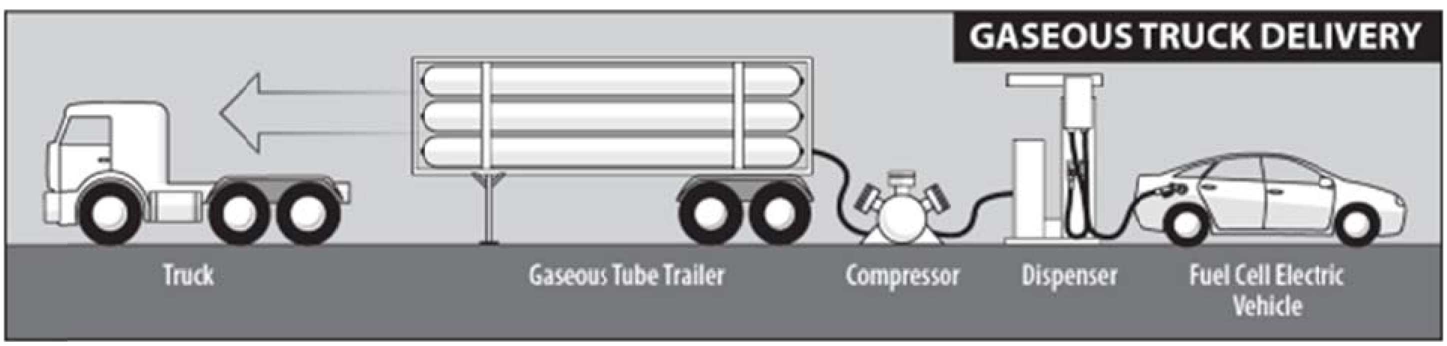

Figure 3: Demonstration Fleet Fuelling Pathway With Delivered Gaseous Hydrogen (image coourtesy of NREL)

4. Phase II – Pilot Deployment (5 to 20 buses)

At the next stage, a pilot deployment of fuel cell buses is typically in the range of five to twenty buses. Transit agencies and bus operators at this stage of deployment have conducted an initial evaluation of fuel cell technology. Bus operators recognize the business and performance benefits of fuel cell buses and are integrating the zero-emisision buses into their normal operations.

At this level of consumption (125-500 kilograms per day), the installation is not temporary, and the dispenser will usually be set in line with the compressed natural gas (CNG) or diesel buses in order to maintain fuelling operations continuity.

4.1. Fuelling Solution

In terms of hydrogen production, delivered liquid hydrogen storage is often the most economical model for this size of fleet. The hydrogen is produced at a large-scale industrial facility and delivered via crygenic transport trailer for storage on-site. It is often produced through large-scale steam methane reforming or wind power electrolysis. Liquid hydrogen is sometimes used in combination with electrolysis, where some agencies have integrated solar panels with an electrolyser to produce some portion of the required fuel through a renewable source. The block diagram below illustrates the delivered liquid hydrogen fuelling pathway.

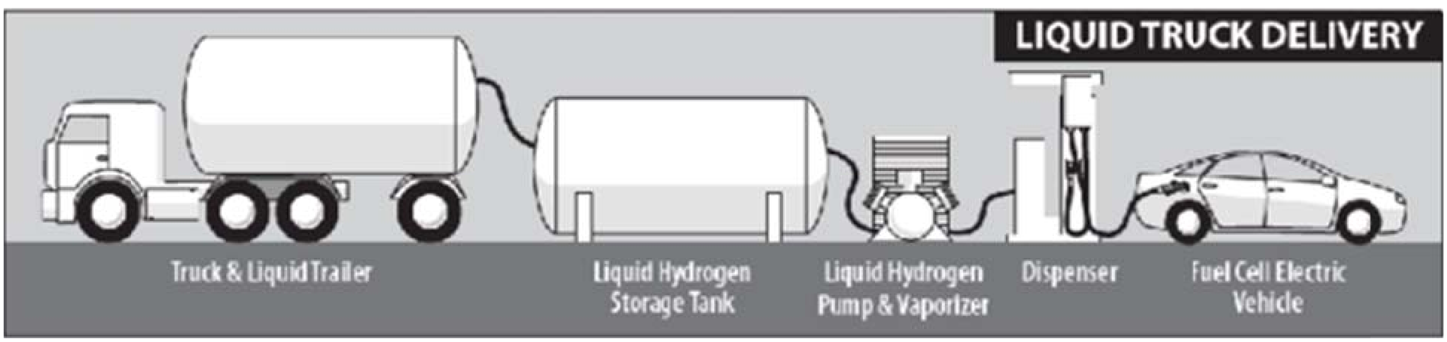

Figure 4: Pilot Deployment Fleet Fuelling Pathway With Delivered Liquid Hydrogen (image courtesy of NREL)

5. Phase III – Commercial Deployment (>20 buses)

Commercial deployment is typically greater than twenty fuel cell buses. Transit agencies at this stage in deployment have fully embraced zero-emission fuel cell bus technology and are ready to invest in the fuelling infrastructure to support a significant fleet of buses. One of the advantages of fuel cell electric buses over other zero-emission technologies is the ability to scale up the fuelling infrastructure without requiring substantial changes to vehicle operations or substantial modifications to the electrical grid.

5.1. Fuelling Solution

There are two viable fuelling pathways at this scale of hydrogen production: 1) delivered liquid hydrogen, or 2) on-site hydrogen production through steam methane reforming (SMR); including various combinations of the two.

The equipment used for a commercial liquid hydrogen fuelling station would be similar to that illustrated in Figure 4, with additional dispensers to allow streamlined fuelling operations. Depending on the size of the storage tank, liquid hydrogen delivery would be 1 -2 times per week, during off-peak hours.

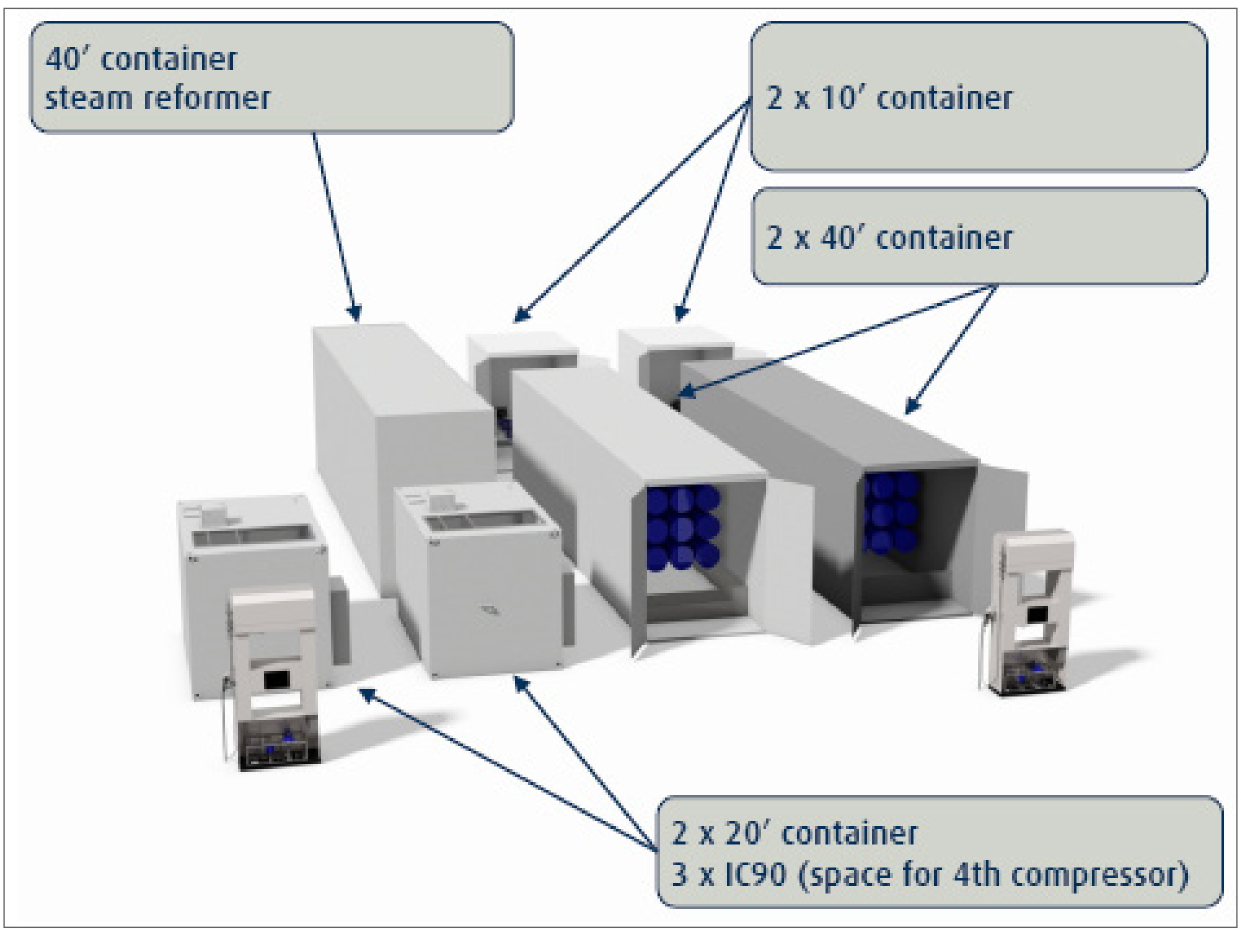

Figure 5: Pilot Deployment Fleet Fuelling Pathway with On-site SMR (image courtesy of The Linde Group)

The other viable option at this scale is on-site hydrogen production using natural gas through a process known as steam methane reforming (SMR). This production process is based on the "cracking" of compressed natural gas (methane) to produce hydrogen fuel. For agencies with compressed natural gas bus fleets, this is often an attractive option as the fuel feedstock (methane) is common for both bus technologies. Both fuelling pathways are suitable at this level of consumption, with the most economical dictated by geography, where the distance to the hydrogen production facility will impact the cost per kilogram of fuel. Figure 5 illustrates the on-site SMR fuelling pathway.

6. Real-World Applications at European Bus Depots

6.1. Trailer Delivery of Gaseous Hydrogen from SMR in London, UK

Air Products provides hydrogen fuel and fuelling facilities for the fleet operating in London at Transport for London. The hydrogen is generated in the Netherlands and then shipped across the English Channel as liquid hydrogen and trucked to the transit bus maintenance facility. A novel liquid hydrogen tanker has been developed by Air Products, which can dispense high-pressure hydrogen into banks of hydrogen cylinders at a filling station. This vehicle is able to supply high-pressure hydrogen to London's filling station, thereby minimising the use of compressors. As of July 2015, more than 5,600 fillings had taken place, with over 96,000 kilograms of hydrogen supplied. London operator, Tower Transit, is able to fill a bus from empty in less than ten minutes on average.

Figure 6: Hydrogen Fuelling Station for London Fuel Cell Bus Fleet (courtesy of First)

6.2. Electrolysis-Based Fuelling Station in Oslo, Norway

In June 2016, Oslo announced it would reduce the city's carbon emissions 50% by 2020 and 95% by 2030. Ruter, the public transport authority in the region, is supporting that initiative by ensuring that all public transport in Oslo runs on only renewable energy by the end of 2020.

The hydrogen refuelling station for the first five fuel cell buses deployed in Oslo by operator Ruter is owned and operated by Air Liquide Norway. Hydrogen is generated from water via electrolysis, using two HySTAT™ 60 electrolyzers provided by Hydrogenics Corporation. The hydrogen station has a generating capacity of 250 kilograms per twenty-four hour period to refuel five buses with 35 kilograms each[1]. The refuelling pressure is 350 bar. All five buses are filled within a two hour period overnight. Because it is generated from renewable sources, the hydrogen fuelling station delivers 100% certified green hydrogen.

1. CHIC Project. "The Oslo hydrogen refuelling station" chic-project.eu http://chic-project.eu/uncategorized/oslo-hydrogen-refueling-station (accessed December 16, 2016).

Figure 7: Hydrogen Fuelling Station at the Rosenholm Bus Garage in Oslo (image courtesy of CHIC)

6.3. Trailer Delivery of Gaseous Hydrogen from By-Product Source in Cologne, Germany

Regionalverkehr Köln GmbH (RVK), the public transport operator in the region of Cologne, has set an ambitious target to replace its entire diesel bus fleet with alternative powertrains. Four fuel cell buses operate 12 to 16 hours per day; Cologne is located at a center of chemical production which also happens to be a good source of hydrogen for the bus fleet. At several chemical plants in the area (three Bayer plants, one Degussa plant, and one Vinnolit plant) hydrogen occurs as a byproduct of chemical processes. This hydrogen is captured and delivered to a fuelling station designed by Air Products using a modular system, which allows for easy expansion or relocation.

Figure 8: Hydrogen Fuelling Station in Cologne, Germany (image courtesy of CHIC)

7. Paying for Hydrogen Infrastructure in the European Union

Transit agencies and bus operators struggle with their internal budgets to meet daily service levels. It would be unreasonable to expect these agencies/operators to make multimillion-dollar investments in hydrogen infrastructure without support from other stakeholders.

Funding provided by the European Fuel Cells and Hydrogen Joint Undertaking (FCH JU) has contributed significantly to the development of hydrogen fuelling infrastructure for fuel cell bus fleets. The FCH JU is a unique public-private partnership supporting research, technological development, and demonstration activities in fuel cell and hydrogen energy technologies in Europe. Through a series of funded projects, the FCH JU has been instrumental in demonstrating on a large scale the feasibility of fuel cell bus fleets. To date, the FCH JU has supported the development of 20 hydrogen fuelling stations in Europe[2].

2. Fuel Cells and Hydrogen Joint Undertaking. "FCH JU – Key to Sustainable Energy and Transport..." www.fch.europa.eu http://www.fch.europa.eu/sites/default/files/FCH-booklet-2016.pdf (Accessed December 16, 2016).

The FCH JU is also undertaking research projects to resolve the knowledge gap for the establishment of large-scale hydrogen refuelling infrastructure for fuel cell buses. One such project is New Bus Refuelling for European Hydrogen Bus (NewBusFuel). The overall aim of NewBusFuel is to introduce the technologies and engineering solutions required for the refuelling of a large number of buses at a single bus depot. The consortium involves 10 of Europe's leading hydrogen station providers. These partners will work with 12 bus operators in Europe, each of whom has demonstrated political support for the deployment of hydrogen bus fleets. Once complete in 2017, the project will introduce a set of design guidelines for the range of depot fuelling solutions which exist (and their economics).

In addition, funding is available at the national or local level in regions showing leadership in supporting the technology development which is required to allow them to achieve their environmental aims, such as London, Aberdeen, and Hamburg.

8. Transitioning from CNG Buses to Hydrogen Fuel Cell Buses

Unlike battery electric buses that require a total replacement of the existing fuelling infrastructure, fuel cell electric buses allow transit agencies that are currently operating CNG buses to transition to a low and zeroemission fleet mix using a common fuel feedstock (methane) and leveraging the existing infrastructure.

A combination of low-emission CNG buses with zero-emission fuel cell electric buses would demonstrate an "integrated" solution from a common fuelling supply chain under a model that is both economical and scalable to hundreds of buses (perhaps the 'Achilles heel' for battery electric buses).

Hydrogen and compressed natural gas share many of the same characteristics, making implementation easier:

- *Similar codes and standards for the safe handling of Class 2 flammable gasses*
- *Common distribution equipment up to the steam methane reformer; similar piping, compression, gas*
- *storage and dispensing systems*
- *Similar refuelling procedures*
- *Similar regulatory process with fire marshall and other authorities having jurisdiction (AHJ)*
- *Similar leak detection and other safety systems*
- *Similar training and qualifications for technicians*

9. Hydrogen Infrastructure Suppliers

Every transit agency will have unique requirements impacting the choice of fuelling technology. Suppliers of hydrogen infrastructure with experience supporting deployments of fuel cell buses in Europe include the following companies. Contact these companies to find the right solution for each specific property.

SUPPLIER	
AIR PRODUCTS supplies liquid and gaseous hydrogen and a broad portfolio of fuelling infrastructure solutions www.airproducts.com	**McPHY** solutions for the production and storage of hydrogen by combining electrolysers with solid hydrogen www.mcphy.com
AIR LIQUIDE expertise in the entire hydrogen chain (production, storage, and distribution) www.airliquide.com	**NEL HYDROGEN** delivers solutions to produce, store and distribute hydrogen from renewable energy www.nelhydrogen.com
AREVA H2-GEN manufacturer of Proton Exchange Membrane (PEM) electrolysers www.areva.com	**SHELL** hydrogen filling stations www.shell.com
ITM POWER manufacturer of integrated hydrogen energy systems www.itm-power.com	**WATERSTOFNET** develops hydrogen projects to enable zero-emission transport in Flanders and the Netherlands www.waterstofnet.eu
THE LINDE GROUP solutions for hydrogen production, storage, and distribution for fleet applications www.the-linde-group.com	

10. Cost of Fuelling

With fleets operating at various locations in Europe (see Appendix II), it is now possible to provide guidelines for consideration when deploying hydrogen infrastructure to support fleets of various sizes and assign some associated costs to these parameters. Fuel cell bus programs undertaken by the FCH JU have consumed more than 42,900 kilograms of hydrogen, with greater than 2,500 refuelling events in 2015 alone. In the latest demonstration projects, the average fuel consumption of a 12-meter bus was 9 kilograms of hydrogen per 100 kilometers, which is equivalent to 30 litres of diesel. This makes a fuel cell bus 26% more efficient than an equivalent diesel bus.

A useful metric for bus operators to compare hydrogen and diesel infrastructure costs is the average hydrogen cost (€/kg), which incorporates all capital and operating costs. The goal for current FCH JU funded programs is ≤ 9.0 €/kg dispensed (excluding taxes). For cost parity with diesel, a hydrogen fuel price of €5- 6/kg is widely accepted as the target for industry, as this is the level which allows parity with diesel costs for today's buses. With this price, a ten year commitment to hydrogen consumption is required. A line of site to this target is most achievable in countries such as Denmark, Norway and Germany, which have high adoption of renewable energy sources and a fair tax system on the electricity grid.

In addition to the type of hydrogen fuel production (SMR, electrolysis), there are several variables such as on-site vs. centralized production, fuel distribution method, buffer storage, dispensing rate, etc. that have a major impact on the fuelling infrastructure costs. Industrial hydrogen gas suppliers indicate that these values are an estimate only and must be validated for each proposed site.

11. Conclusion

Transit agencies and bus operators who start to engage with hydrogen buses for the first time generally report a lack of information as the first barrier to adoption. This paper aims to provide an introduction to the hydrogen supply alternatives available to transit agencies and bus operators deploying fuel cell bus fleets.

As hydrogen infrastructure technology continues to mature, improvements will be made in solutions available to transit agencies. Hydrogen produced from renewable sources, such as solar, wind or biomass will become more prevalent and economical. While this study provides a guideline for transit agencies transitioning to hydrogen fuel, agencies are encouraged to contact a regional gas supplier (as outlined in Section 9) to determine the ideal solution for a particular scenario.

Appendix I – Hydrogen Supply Alternatives

Hydrogen is one of the most abundant elements, but it is rarely found in its purest form. Hydrogen fuel can be obtained from many sources, including natural gas, biogas or other hydrocarbon fuels, as a by-product of chloralkali production, or from water through electrolysis. The base substance dictates the production process chosen. Each of these production methods has a varying environmental impact.

Hydrogen can be produced in large “central production” plants and transported to the point of end-use. Liquid hydrogen is the most cost-effective form of hydrogen to transport. Hydrogen may also be produced in smaller “distributed production” facilities, very near or at the point of end-use. Delivery methods for hydrogen fuel are determined by the production volume and delivery distance, as shown in Figure 9.

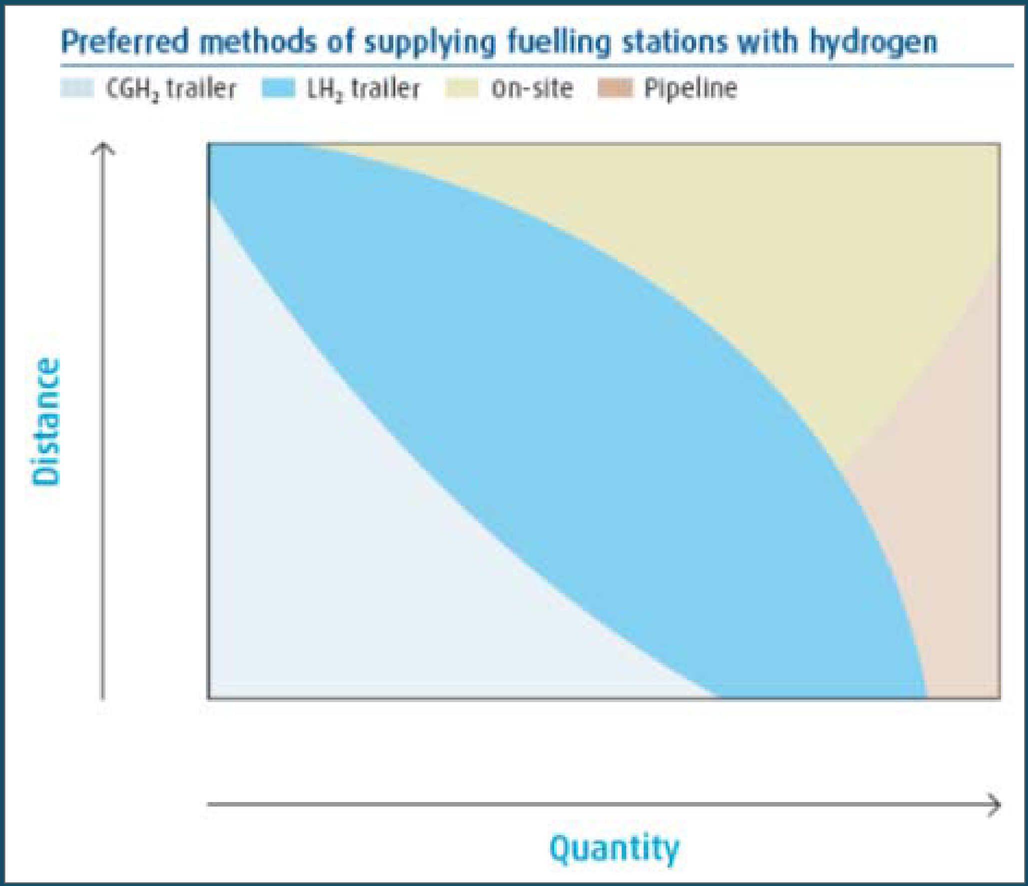

Figure 9: Preferred Hydrogen Supply Methods (image courtesy of The Linde Group)

There are various feasible hydrogen fuel production and delivery methods for transit agencies. The choice is most often based on fleet size and location.

11.1. Compressed gaseous hydrogen in tube trailers

Compressed hydrogen tube trailers are typically used in low-volume commercial applications or temporary demonstration projects. Trucks transport vessels of compressed gaseous hydrogen for short distances to deliver hydrogen from a central facility. These tube trailers provide convenient and portable fuelling solutions but are typically less efficient than permanent liquid hydrogen installations. Limitations include the low storage capacity requiring frequent delivery and the low pressure of hydrogen delivered, which requires additional compression at the fuelling station site. Nominal emissions are associated with the delivery to the site by internal combustion engine transport trucks.

Figure 10: Hydrogen Delivered Via Tube Trailer by Praxair

11.2. Liquid hydrogen delivery and storage

Liquid hydrogen installations are an ideal solution for high-volume, permanent commercial installations, such as fuelling stations for fuel cell transit bus fleets. The energy density of liquid hydrogen is considerably higher than that of compressed hydrogen and is therefore generally a more cost-effective solution for large-scale use, as fewer journeys are necessary to transport the same quantity of energy. The liquid hydrogen is then vaporized to a high-pressure product for use at the bus depot. Again, some nominal emissions are associated with the delivery to the site by internal combustion engine transport trucks.

Figure 11: Liquid Hydrogen Storage by Air Liquide

11.3. On-site steam methane reformation

Large scale SMR is the most cost-effective method of hydrogen production today. Medium-scale reformers are available for producing on-site hydrogen from natural gas for hydrogen bus fleets. Fully skidded, modular designs allow for low-cost installation at the bus depot in a compact footprint. Also, renewable natural gas (RNG or biogas) can be a feedstock for the reformer to create renewable hydrogen in the SMR process. Although the SMR technology is popular and can be renewable, there are some emissions as a result of the process. In regions with strict requirements regarding zero-emission solutions, this option may not be suitable.

Figure 13: Air Products PRISM On-Site Hydrogen Generation System

11.4. On-site electrolysis

Electrolysis is a promising option for hydrogen production from renewable resources. Electrolysis is the process of using electricity to split water into hydrogen and oxygen. The resulting hydrogen is stored until it is needed to fuel the bus. Hydrogen produced via electrolysis can result in zero greenhouse gas emissions, depending on the source of the electricity used.

Figure 12: ITM Power's HFuel Unit Generates Hydrogen Gas From Water By Electrolysis

11.5. By-product sources

Certain chemical processes, such as chlorine and sodium chlorate production, generate hydrogen as a by-product. In cases where this by-product hydrogen is flared (vented) or burned for its heating value, the chemical producer is failing to maximize the full value of this hydrogen. This hydrogen can be captured and transported to the bus depot via trailer. The total available hydrogen from global byproduct sources is estimated to be sufficient to produce 100,000 megawatts of power[3].

3. Fuel Cell and Hydrogen Energy Association. "Waste/By-Product Hydrogen." energy.gov http://energy.gov/sites/prod/files/2014/03/f12/waste_cox.pdf (accessed December 15, 2016).

The table below summarizes the key characteristics of each hydrogen supply alternative.

TOPIC	Compressed gaseous hydrogen	Liquid hydrogen	On-site SMR	On-site electrolysis	By-product source
Overall	Good for volumes <125kg/day	Excellent for large volumes	Good supplement for large volumes	Good supplement for large volumes	Good supplement for large volumes
Distribution Costs	High; price drastically affected by location	Nominal; range flexibility	None	None	Nominal; range flexibility
Price Volatility	Cost dependent on fuel prices but can be set with contract	Cost dependent on fuel prices but can be set with contract	Cost dependent on maintenance and fuel costs	Cost dependent on maintenance and electricity costs	Cost dependent on fuel prices but can be set with contract
Infrastructure Costs	Lower	Higher	Depends on production capacity	Depends on production capacity	Lower
Carbon Emission Reductions	Renewable hydrogen available at higher cost	Renewable hydrogen available at higher cost	Renewable biogas available at higher cost	Renewable energy is available at higher cost or renewable energy infrastructure can be installed on-site	Renewable hydrogen sources

Appendix II – Recent European Fuel Cell Bus Fleets[4]

TRANSIT AGENCY LOCATION	FUEL CELL BUS FLEET	HYDROGEN SOURCES AND SUPPLY PATHWAYS	HYDROGEN INFRASTRUCTURE MANUFACTURER
Aargau, Switzerland	5 buses	On-site production from renewable sources and regular trailer delivery from by-product source	Air Liquide
Aberdeen, Scotland	10 buses	On-site production from renewable sources	BOC (Linde Group)
Antwerp, Belgium	5 buses	Trailer delivery of gaseous hydrogen from by-product source (nearby chemical plant)	Supplied by Nel Hydrogen, now owned by PitPoint Clean Fuels
Bolzano, Italy	5 buses	On-site production from renewable sources	Linde Group
Cologne, Germany	4 buses	Trailer delivery of gaseous hydrogen from by-product source (nearby chemical plant)	Air Liquide
Eindhoven, Netherlands	2 buses	On-site production from renewable sources	WaterstofNet
Groningen, Netherlands	2 buses	Temporary trailer delivery of hydrogen, with final refuelling station to be built in Delfzijl	PitPoint Clean Fuels, Akzo Nobel
Hamburg, Germany	6 buses	On-site production from renewable sources and regular trailer delivery from by-product source	Linde Group
Karlsruhe, Germany	2 buses	On-site production from biomass and regular trailer delivery from conventional sources	Karlsruhe Institute of Technology (KIT)
London, UK	8 buses	Trailer delivery of gaseous hydrogen from SMR	Air Products
Milan, Italy	3 buses	On-site production with a mix of electricity and trailer backup delivery	Linde Group
Oslo, Norway	5 buses	On-site production from renewable sources	Air Products
San Remo, Italy	5 buses	On-site production from renewable sources and trailer backup delivery	Air Liquide
Stuttgart, Germany	4 buses	On-site production from renewable sources	Linde Group

4. Fuel Cells and Hydrogen Joint Undertaking. "Clean Hydrogen in European Cities 2010-2016." www.fch.europa.eu http://www.fch.europa.eu/news/chic-final-report-tool-cities-and-bus-operators (accessed December 15, 2016).

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